Energy Conversion and Management 171 (2018) 528–540

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Optimal daily generation scheduling of large hydro–photovoltaic hybrid power plants

Bo Ming, Pan Liu*, Lei Cheng, Yanlai Zhou, Xianxun Wang

State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
Hubei Provincial Collaborative Innovation Center for Water Resources Security, Wuhan 430072, China

ARTICLE INFO

Keywords:
Hydro–photovoltaic hybrid plant
Generation scheduling
Robust optimization
Three-layer nested approach

ABSTRACT

Joint operation of large-scale renewable energy sources (e.g., hydro and solar) has become a trend in modern power systems, and more operators of existing hydropower reservoir systems are adopting it. This study aimed to improve guidance for the daily generation scheduling of a large hydro–photovoltaic (PV) power plant. First, a robust optimization model that accounts for uncertain PV power generation was formulated, in which the delivered power output of the hybrid system and hydro unit status are robust decision variables. To deal with the complexity of the model solution, a three-layer nested framework was proposed to solve the generation scheduling problem in a hierarchical structure. In the outer layer, a direct search algorithm optimizes the delivered power output of the system, aiming to maximize energy production while satisfying specified load characteristics. In the middle and inner layers, a cuckoo search algorithm and dynamic programming technique optimize the hydro unit status and load dispatch strategies, respectively, with the objective of minimizing water consumption. Finally, a decision interval on delivered power output of the system was derived by relaxing the load characteristic constraint. Results for a case study using China's Longyangxia hydro–PV power plant indicated that the robust optimization model and the three-layer nested approach could provide effective power generation plans for the hybrid system within a reasonable time. Compared with actual operation, the power generation plans could increase energy production of the hybrid system by 1.9% while decreasing total online time of the hydro units by 9.7%. Therefore, the proposed method could improve guidance for the hydro–PV power plant's generation scheduling. In practice, conjunctive use of the power generation plan and the decision interval could also inform flexible decision-making for plant operations management.

1. Introduction

Global climate change is the main driving force behind worldwide interest in the generation of bulk electrical energy from renewable energy sources (RESs) [1]. However, the increasing penetration of non-dispatchable RESs into traditional power grids exacerbates difficulties for system security and stability [2]. Joint operation of multiple power sources (e.g., hydro and solar) has been regarded as one of the most cost-efficient measures for promoting the integration of RESs [3].

Hybrid energy systems (HESs), which aggregate two or more power sources, are becoming popular since they can provide greater balance in the energy supply as well as increased system efficiency [4,5]. Typical HESs include hydro–wind systems [6,7], hydro–photovoltaic (PV) systems [8,9], hydro–solar–wind systems [10,11], and hydro–thermal–-wind systems [3,12]. The hydro–PV system is among the most widely used HES because hydropower can be regulated rapidly and solar energy is the largest available type of RES [13,14]. Regions that are rich in both hydro and solar resources, such as Northwest China, are particularly suitable for development of large hydro–PV systems.

Research regarding the hydro–PV system mainly focuses on exploration of time complementarity between hydropower and PV power [15–17], optimization of the system configuration [9,17–19], and plant operations management [20–22]. For the first aspect, Beluco et al. [15] found that the better temporal complementarity between hydro and solar energy of a hydro–PV plant could help decrease energy supply interruptions to consumers. François et al [16] revealed that the combination of solar power and run-of-the-river power could decrease energy balance variability in northern Italy. Kougias et al. [17] found that the complementarity between small hydropower plants and solar PV systems could be improved by optimizing the installation azimuth and tilt of the PV system. These findings demonstrated the advantages of the hydro–PV system in meeting energy demand, which can be further improved by optimizing the configuration of the hybrid system. For example, Glasnovic and Margeta [9] formulated a sizing model that

* Corresponding author.
E-mail address: liupan@whu.edu.cn (P. Liu).

https://doi.org/10.1016/j.enconman.2018.06.001
Received 6 March 2018; Received in revised form 29 April 2018; Accepted 1 June 2018
0196-8904/ Published by Elsevier Ltd.

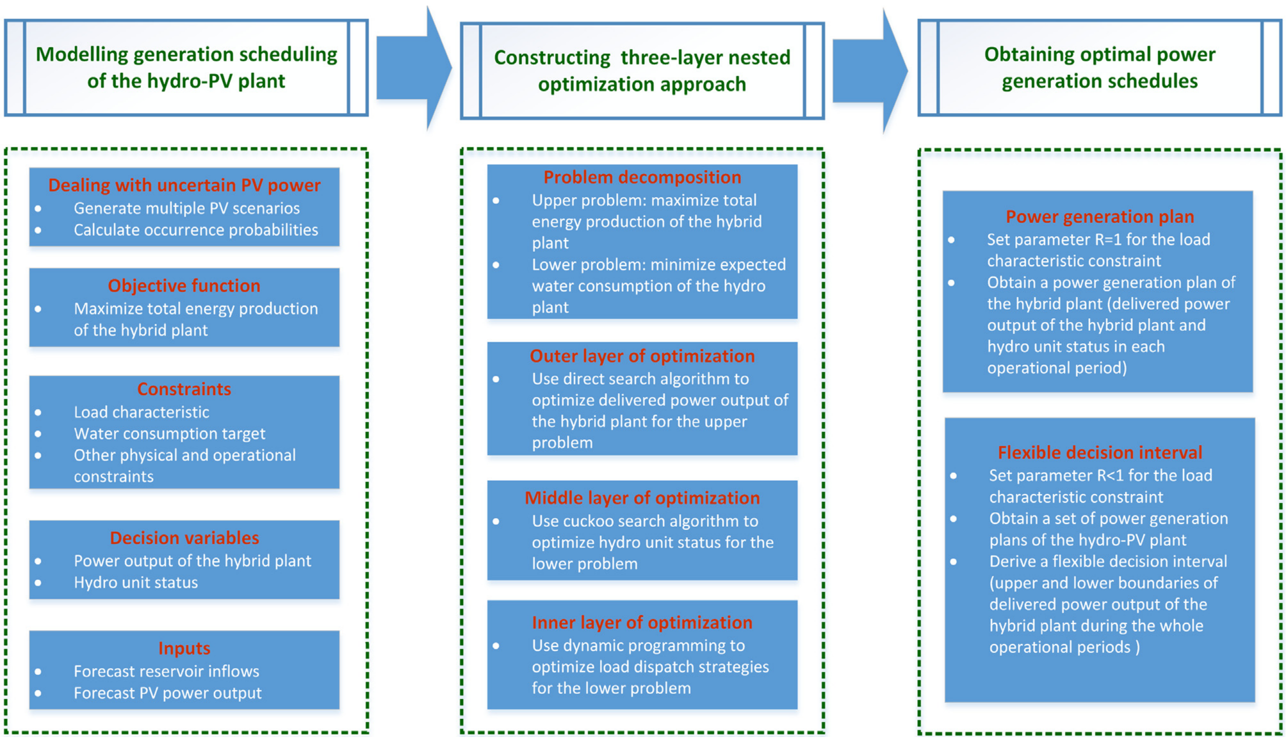

Fig. 1. Flowchart for making generation schedules for large hydro–PV hybrid plant.

sought the best operational performance of the PV plant to satisfy all energy demands. Fang et al. [18] proposed a method to determine the optimal size of a PV plant by maximizing its net revenue. Jurasz and Ciapała [19] developed a mixed integer mathematical model to determine configuration parameters for a hydro–PV system by simulating its operation. Ming et al. [22] optimized the size of a PV plant by integrating long- and short-term operational decisions. With respect to operations management of large hydro–PV systems, there were also related studies. For example, An et al. [21] presented the general principle for the hydro–PV plant short-term scheduling. Li and Qiu [20] developed long-term operating strategies for a hydro–PV plant using multi-objective optimization. However, to the best of the authors' knowledge, the short-term generation scheduling of large hydro–PV power plants has not been studied in the literature. As China and other countries continue integrating stochastic PV power into existing large hydropower reservoirs, there is an urgent need for effective operating strategies to guide the daily generation scheduling of the hydro–PV plant (DGSHP).

The basic task of the DGSHP problem is to determine the power output of each hydro unit over the whole operating horizon so as to maximize total energy production of the hybrid system while satisfying specific load characteristics. This task should incorporate reservoir inflow and PV power forecasts to inform the generation scheduling model, which inevitably introduces uncertainties into decision-making process. In addition, such models contain stringent constraints and a large number of decision variables, which make them complicated to solve.

To cope with optimization problems under uncertainty, various models have been proposed, including the stochastic optimization model [23], robust optimization (RO) model [3], probabilistic optimization model [24], and interval optimization model [25]. Due to its high computational efficiency, modelling flexibility, and ability to provide reliable solutions that are feasible for any realization of all parameters within the uncertainty set, RO has been widely used in power system planning and operation [26–28]. In this study, RO was used to deal with the DGSHP problem having uncertainty.

Generally, approaches for solving the DGSHP problem can be classified into two categories: conventional programming methods, such as dynamic programming (DP) [29] and mixed integer linear programing [30], and evolutionary algorithms (EAs), such as genetic algorithms [31] and particle swarm optimization [32]. However, almost all algorithms have limitations in terms of their solution efficiency and accuracy [33,34]. Thus, exploration of effective solution algorithms is still essential for effectively addressing the DGSHP problem.

This study was conducted to provide timely and reliable decision support for DGSHP. First, a RO model that considers uncertain PV power generation was developed, in which hybrid plant output and unit status are robust decision variables. To account for the peak-shaving role of the hydro–PV plant in the power system, a load characteristic constraint was incorporated into the model. Second, a three-layer nested approach was proposed based on the idea of divide-and-conquer. In this approach, a direct search algorithm (DSA), a cuckoo search (CS) algorithm, and DP were fused together to optimize decision variables in a hierarchical structure. Finally, by relaxing the load characteristic constraint, a decision interval for the power output of the hybrid plant was derived to provide flexible options for the power system operator.

The rest of the paper is structured as follows: Section 2 provides details of the methodology, including the DGSHP model, three-layer nested approach, and evaluation indices of the power generation plan. Section 3 introduces a case study using China's Longyangxia hydro–PV plant, and Section 4 gives and discusses results. Finally, conclusions are drawn in Section 5.

2. Methodology

The methodology used here aims to develop a power generation plan as well as a decision interval for a large hydro–PV plant to assist operations management by the power system operator. Fig. 1 shows a flowchart for making generation schedules for a large hydro–PV plant.